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Simplified Large Area Glancing Incidence Focussing System for X-rays and Neutrons

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Abstract:

Separation of the mechanical constraints associated with surface smoothness and surface orientation greatly facilitates construction of large area glancing incidence focussing systems, for x-rays and neutrons.

A series of workers have pursued the goal of a feasible x-ray focussing system (1,2), culminating in the invention of a practical high resolution x-ray telescope by Giacconi and Rossi (2,3). Their instrument is capable of 1 arc second bar resolution (4). In all such systems to date, the goal has been resolution. The reflecting surfaces are oriented for focussing and polished for reflection by the same series of operations.

In these instruments, x-rays are reflected from polished surfaces at small glancing angles of incidence, e.g. 40 arc minutes, from each of two reflector stages. Use of an even number of stages of reflection allows off axis imaging to first order. Because of this geometry, the amount of polished internal area is roughly 200 times as great as the frontal area subtended in the incident beam by the reflecting surfaces. For smaller angles, the internal area becomes quite large.

For many applications, gathering area is more important than angular resolution. In x-ray astronomy, the brightest known source (Sco X-1) presents $\sim$ 75 photons/ cm^2 sec at the top of the earth's atmosphere, in the energy range 1-10 KeV/photon. In Crux is a roughly comparable source. The next weaker is the Crab Nebula, about 5 photons/ cm^2 sec., and THERE ARE BUT a few others down to 1% of Sco X-1. One could use sensitivities far greater than presently achieved. Clearly, effective subtended frontal area is an important parameter for these systems, because of the severe statistical uncertainties associated with small total numbers of detected photons. This is especially true when the total number of events is divided into several categories, as in spectroscopy and polarimetry.

Two distinctly different levels of angular resolution are interesting for x-ray astronomy. For detailed studies of the few sources which may have observable extent, for certain applications of transmission grating spectroscopy, and for locating x-ray sources for optical correspondence, the highest angular resolution feasible can be useful. For x-ray studies of x-ray sources, such as polarimetry, spectroscopy based on counter resolution or filters, sky surveys, and studies of the 'diffuse' background, a very much cruder resolution suffices. An angular resolution of $\frac{1}{4}^{\circ}$ would allow a sky with 10^5 sources to appear as a field of mostly disjoint objects. For these disjoint objects, the accuracy of angular position determination is very greatly enhanced by the high signal to noise ratio possible with a large area x-ray collector. For this reason, large area crude focus x-ray collectors are also useable for optical correspondence work.

The accuracy of orientation of reflecting surfaces necessary to produce a resolution of $\frac{1}{4}^{\circ}$ can readily be obtained by direct machining. Partly for this reason, I designed an x-ray collector in which the operations of producing the reflecting surfaces and of orienting them are separate. In this design, the reflecting surfaces are produced by tension polishing. These polished surfaces are oriented by simple holders, to form a two stage crude focussing system with off axis imaging.

Tension polishing makes use of surface tension to pull smooth a liquid surface. The viscosity of the liquid is allowed to increase slowly over a time long compared to the lifetime of surface waves and the characteristic time of mechanical disturbances. This results in a surface with a high degree of local smoothness. I have used epoxy resin and glass for this purpose (5).

These surfaces were used to support vapor deposited films of gold and nickel, which were selected both for ease of deposition and reflection properties. Reflectivity measurements on the glass supported films have agreed closely with the reflectivity of carefully prepared polished surfaces, and with theoretical values.(5) The epoxy supported films provided reflection. However, geometric problems in the test apparatus have so far prevented accurate measurement of the total reflectivity.(5)

Figure 1 shows an assemble of parellel plates. Interplate spacing is such that the front edge of one plate just shadows the back edge of the next. A set of such plates forms a module capable of deflecting an x-ray beam of cross section nearly the same as the front of the module. Two such modules can be used in cascade.

A ring of module pairs, each pair providing two stages of reflection, can be used to converge radiation to a focal spot comparable in area to the frontal area of a module. Rings of module pairs can be nested to fill a frontal disc. Angles are chosen to deflect the beams from the separate modules through a common focus. Interplate spacing is chosen to satisfy the 'just shadowing' condition.

Figure 2 is a closeup of part of the front of a modular x-ray collector with 4 nested rings of modules (6). Note the dependence of interplate spacing on radial location of each module. The plates are spaced apart by wires. The accuracy of the spacing gives the illusion that the wires can be seen through the plates. Actually, what is seen is a series of reflections of different pieces of different wires deep within the module. The support frame and wire spacers are aluminum. The plates are glass, .1 mm X 75 mm X 18 mm approximate nominal dimensions. The wires are anchored by a room temperature curing silicone elastomer adhesive (General Electric bathtub seal) for vibration resistance. This adhesive is useable after prolonged exposure to high vacuum, and does not outgas rapidly in vacuum after cure. The glass plates are free to expand differently from the supports, to prevent plate warpage. This collector has withstood 35 gravities rms of transverse and axial random vibration, 50–2,000 cps, for five minutes with no breakage. Modules appear able to withstand several hundred g.

Table I gives some pertinent properties of this collector. The sequence of pictures in figure 3 shows the convergence to a focus of the separate beams deflected by the modules in the nested rings, at successive planes from near the back of the collector to the focal plane. These pictures were taken using a parellel beam of visible light, with the test setup shown in figure 4. Figure 5 shows the image of a light source about 40 meters from the collector. The effective area for radiation entering the collector off axis has been measured for visible light. (Fig. 6) Off axis properties for x-rays are somewhat different, because of the dependence of reflection efficiency on both angle of incidence and energy.

The focussing is a geometric property of the system, independent of wavelength for visible and x-ray radiation. X-ray tests, using a vacuum system with the source about 40 meters from the collector, show focussing. The x-ray intensification agreed with calculations based on the visible light focussing properties and the x-ray reflectivity of the surfaces.

Glancing incidence focussing systems in which the mechanical constraints of surface orientation and surface polishing are satisfied separately are very much easier and less expensive to construct than those which use the same processing for both. This approach makes feasible the construction of very large area systems. The performance of this test collector shows that systems with 10^5 cm^2 subtended area can be built. This approach allows a frontal disc to be filled with reflecting surfaces with an efficiency greater than 80%, and an overall frontal x-ray efficiency of greater than 50%. Orienting the reflecting surfaces in modules by direct machining suffices for angular resolutions (bar resolution) of less than 5 arc minutes. The thinness of the reflecting plates allows fair geometric efficiency down to glancing angles of about 1 milliradian. The accuracy of allignment of the plates is enhanced by a slight warp about the long axis of the collector, imparted by slight radial misallignment of the wire spacers.

The highest energy photon which can be focussed is determined by the smallest useable glancing angle, and the limitations of direct machining allow orientation to reflection angles small enough to allow focussing of 15-20 KeV photons. It is interesting to note that neutrons may also be focussed at such small glancing angles.

For direct geometric reasons, the diameter of the useful image plane is about 1/4 to 1/3 of the collector diameter, independent of focal length. The number of resolved elements in the field of view depends only on the focal spot size. In large systems, the size of the module can be chosen to contribute less to the size of the focal spot than does allignment error. From the accuracies which were acchieved in this test collector by direct machining, the number of resolved elements in the field of view of a large collector can be estimated to be greater than 1,000 , using the bar resolution definition.

The effect of statistical signal accuracy on the accuracy with which the angular location of a source can be determined is especially important in x-ray astronomy, because of the availability of direct photon counting techniques. With ~30,000 counts, an isolated source can be located to ~ 1% of the resolution of the x-ray collector, or a few arc seconds. With a large area, crude resolution system, instead of a small area, high resolution telescope, the trade-off between sensitivity and angular accuracy is reserved for the analytic procedures, instead of being frozen into the hardware. Also, it has so far been very much easier to obtain high quantum efficiency in detectors with fairly crude spatial resolution, suitable for use with crude collectors, than in the high spatial resolution detectors required to exploit the resolution of high resolution x-ray focussing systems. The very large effective areas feasible with crude collectors of the type described makes a statistical approach to angular accuracy attractive.

The same concept of separation of mechanical constraints can also lead to conical systems for collecting radiation, whose properties are not much different from those of a modular system.

Large area x-ray collectors can be used in space for x-ray astronomy, and the collector shown in figure 2 was constructed for such use. Possible laboratory applications in imaging and transport systems include high energy photochemistry, plasma studies, Mossbauer effect and mu mesic atom studies, etc.

References and Notes:

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3. NASA Contractor Report NASA CR-717, 'A Laboratory Program to Develop Improved Grazing Incidence X-Ray Optics,' T. Zehnpfennig, R. Giacconi, R. Haggerty, W. Reidy, and G. Vaiana. 1967 American Science and Engineering, Inc., report to Goddard Space Flight Center.
4. R. Giacconi, 'X-Ray Stars,' Sci. Amer., Vol. 217, No. 6, Dec. 1967.
5. In preparation.

6. Construction of this collector funded by NASA Grant NsG-445, Scope B, and by the Joint Services Electronics Program (U. S. Army, U. S. Navy, and U. S. Air Force) under Contract DA-28-043 AMC-00099(E), with permission. Commercial rights reside with Tools for Radiation Research, Inc., a subsidiary of Unified Technology, Inc., 555 5th Ave., New York, N. Y. Patent pending.
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Table I. Selected properties of x-ray collector shown in figures 2 and 4.

mass		17 kg
diameter		35 cm nominal
central opening (for camera)		12.5 cm nominal
focal length		≈ 135 cm
focal spot size		2 cm. nominal
nominal bar resolution		~ 20 arc minutes
number of resolved elements in field of view (nominal, bar resolution)		~ 50
effective area for x-rays	500 eV	≈ 140 cm^2
(undegraded reflecting	1000 eV	≈ 120 cm^2
surfaces)	1,500 eV	≈ 70 cm^2
geometric area subtended by reflectors in incident beam		≈ 275 cm^2

Captions:

Fig.1 Parallel plate assembly to deflect x-ray beam (one module).

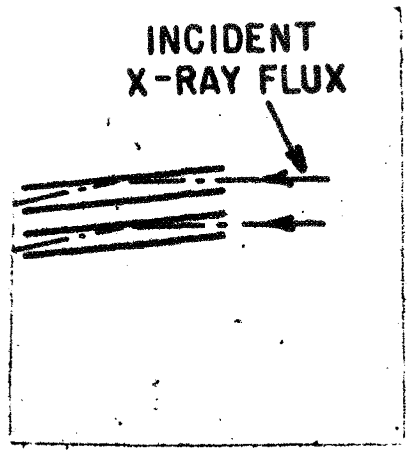
Fig 2. Closeup of part of front of modular collector with 4 nested rings of modules: note dependence of interplate spacing on radial location of module.

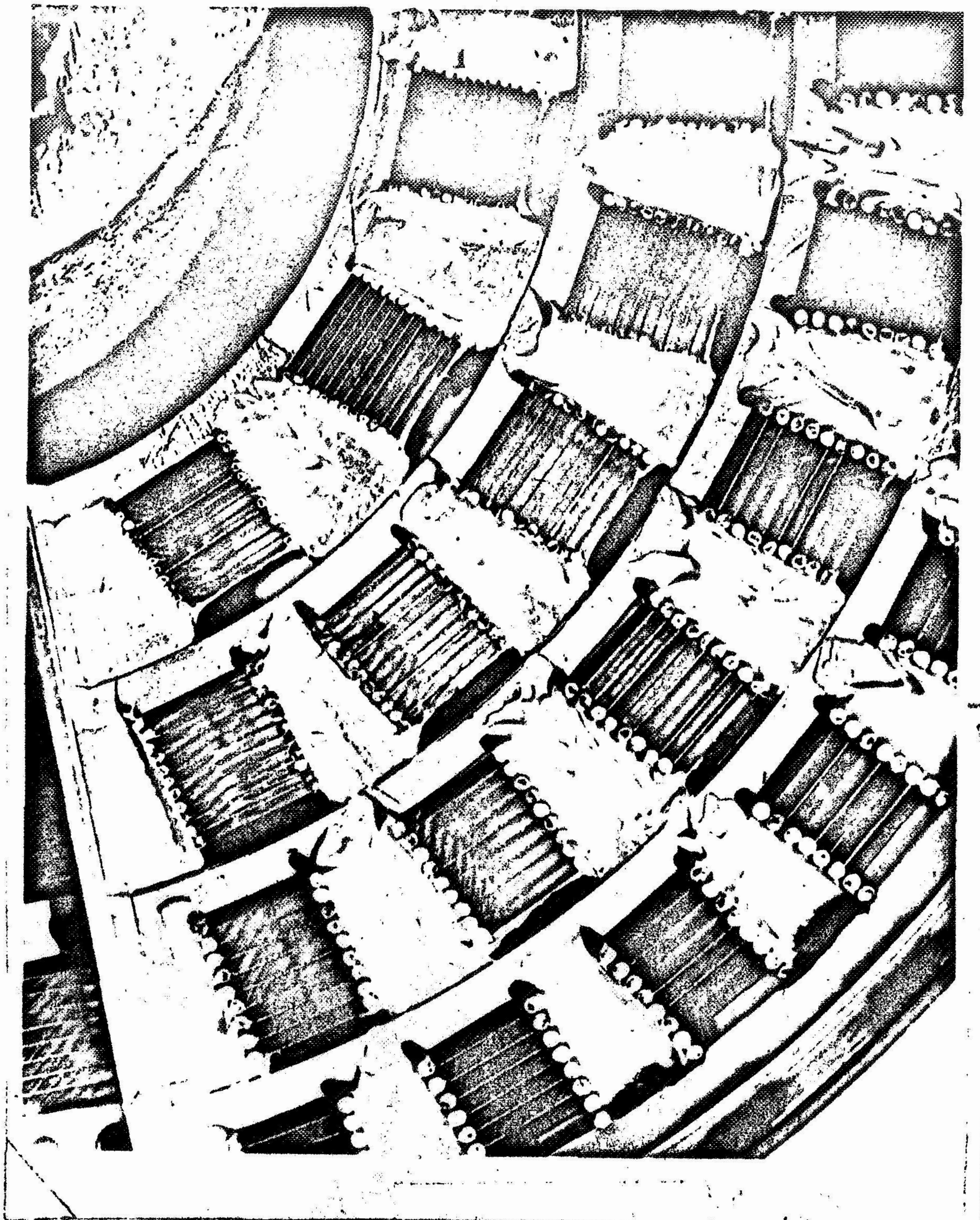
Fig.3. Image for parallel on-axis beam of visible light; successive frames show convergence to focus.

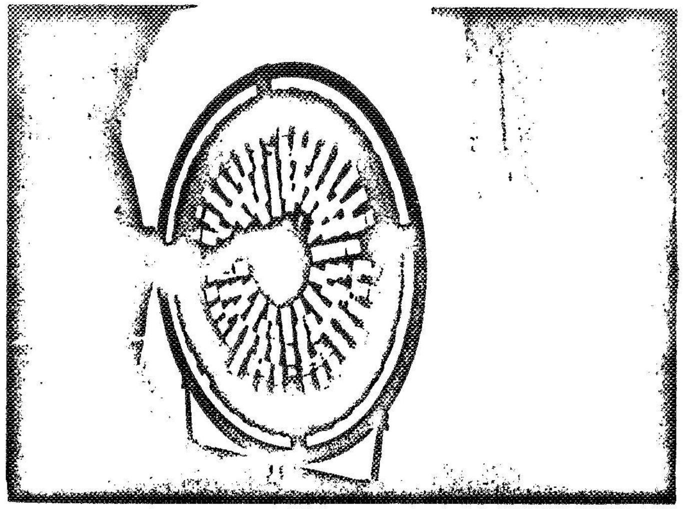
Fig.4. Optical test setup. Rear of collector is directly visible; front is partly visible in parabolic beam-forming mirror.

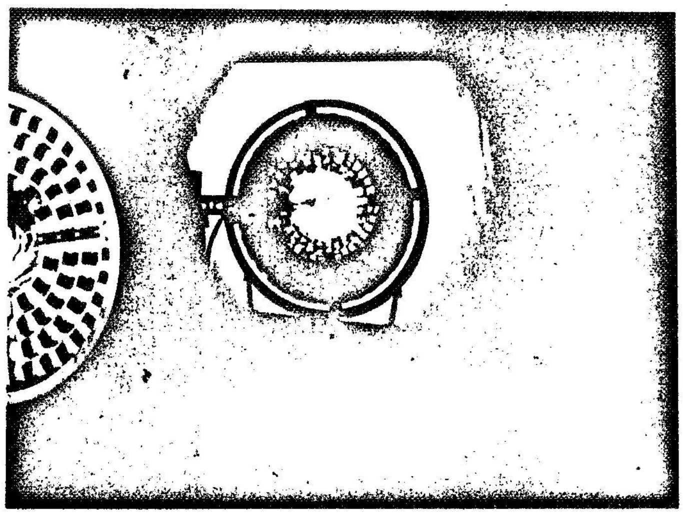
Fig.5. Image of light source ≈40 meters from collector. Circles are ≈1.25 cm. diameter.

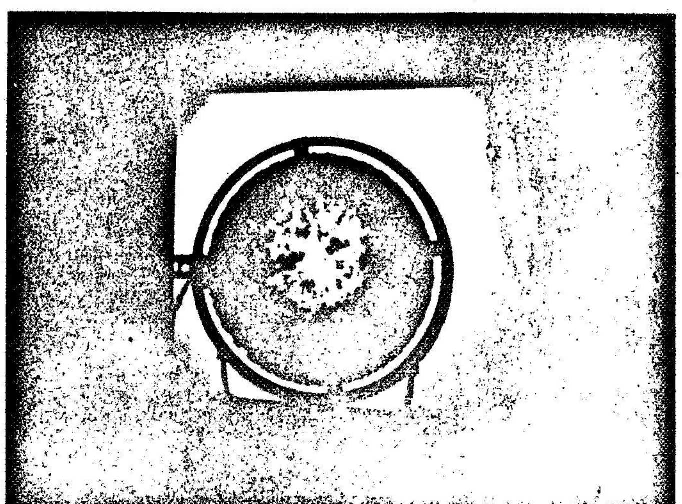
Fig.6. Effective area for beam entering off-axis, for visible light: Shows geometric obscuration of reflecting surfaces.


INCIDENT
X-RAY FLUX









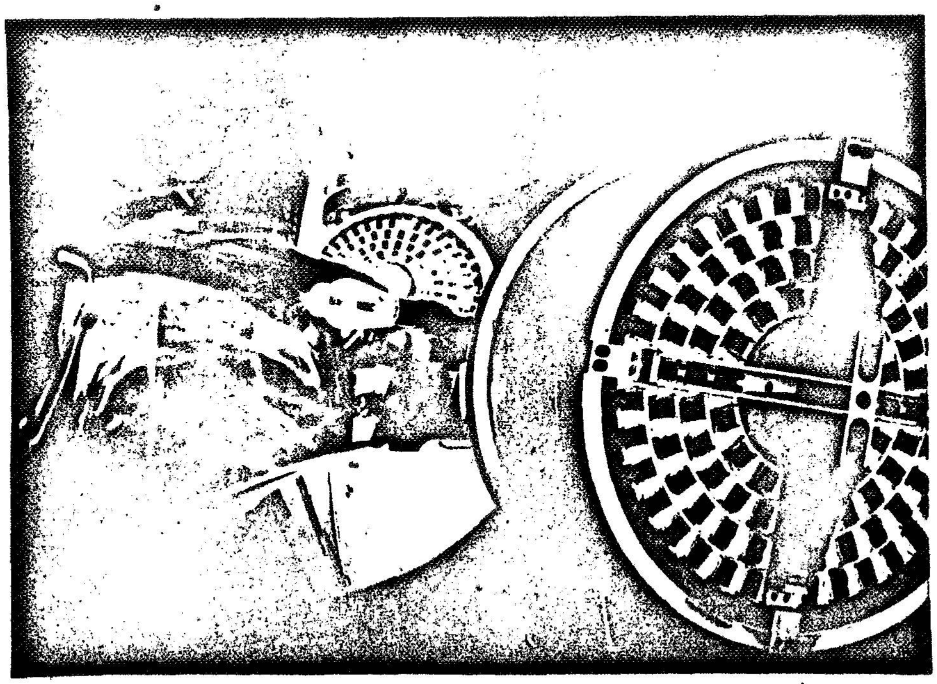


FIG 4

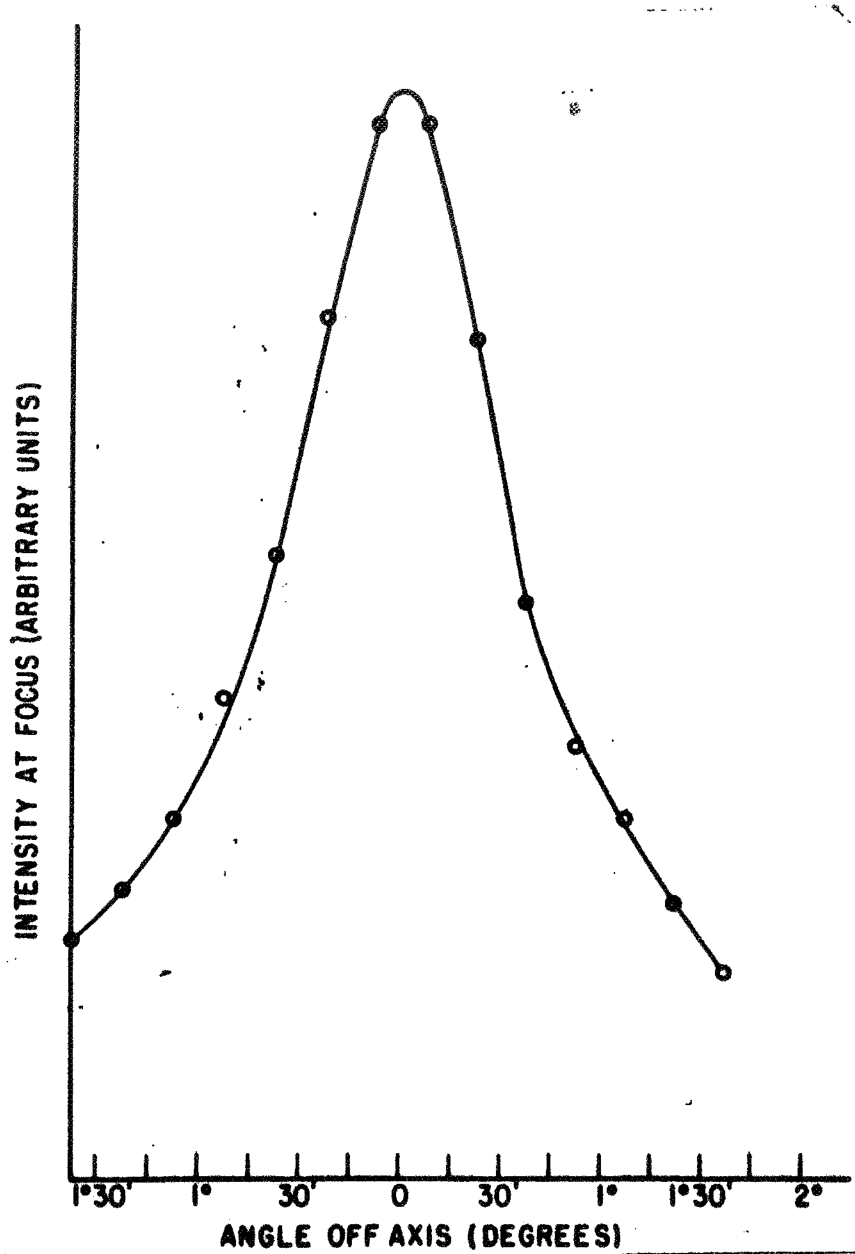

INTENSITY AT FOCUS (ARBITRARY UNITS)
1°30'
1°
30'
0
30'
1°
1°30'
2°
ANGLE OFF AXIS (DEGREES)

FIG 5